TOP JETS AT LHC

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Outline

* Top Jets (Jets initiated by tops)
* Jet Mass Distribution
* QCD Jet Background (due to light quarks)
* Jet Functions (leading contribution to JMD)
* Ex: SM tt vs. di-jet (+detector effects & maximum likelihood fits)
* Jet Sub-structure

Top Jets

Purely Hadronic

Hadronic BR ~2/3

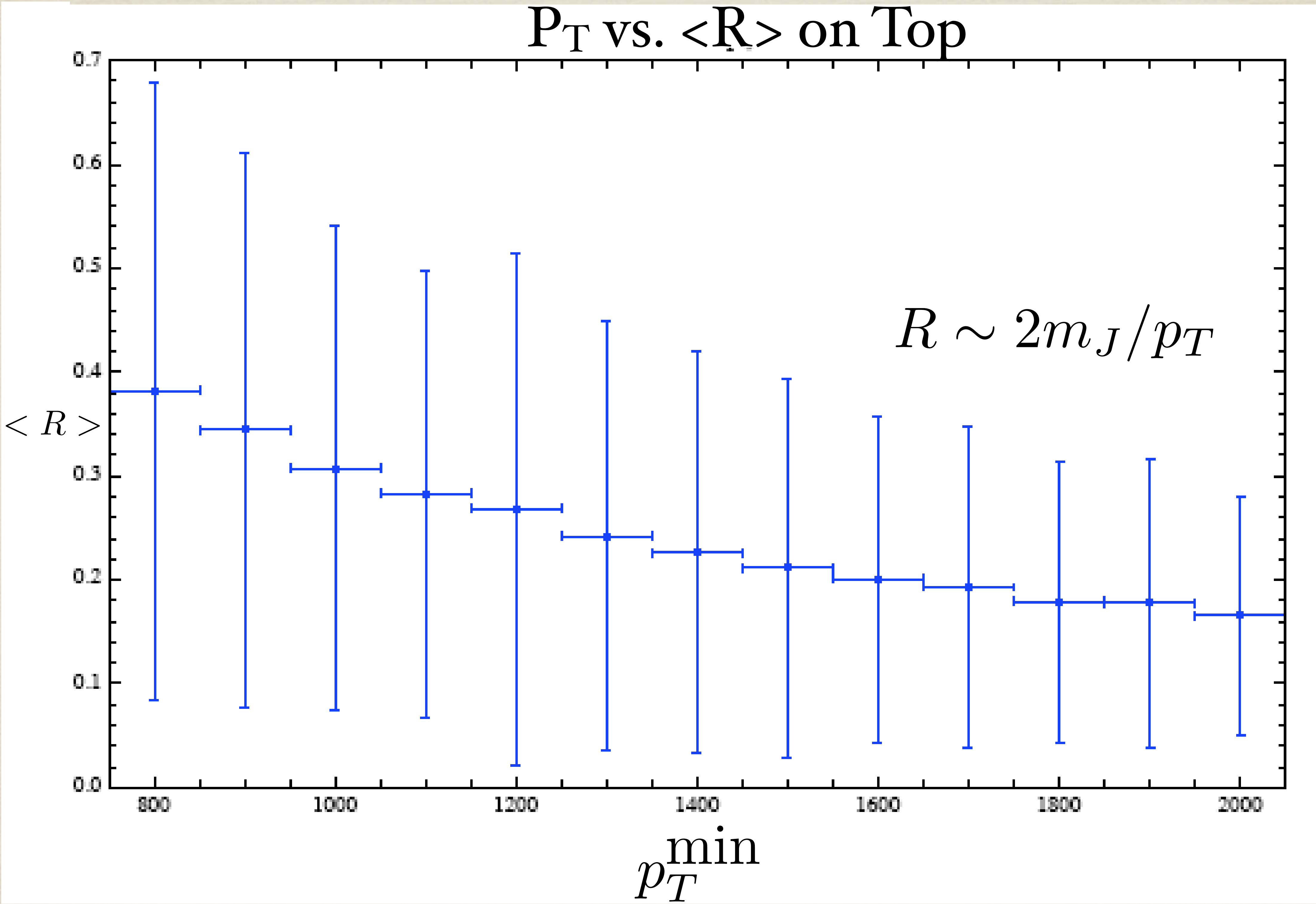
What happens when top decay is Highly boosted ?

Final states become highly collimated

Focus on Top Jet Mass Distribution.   Mass Tag

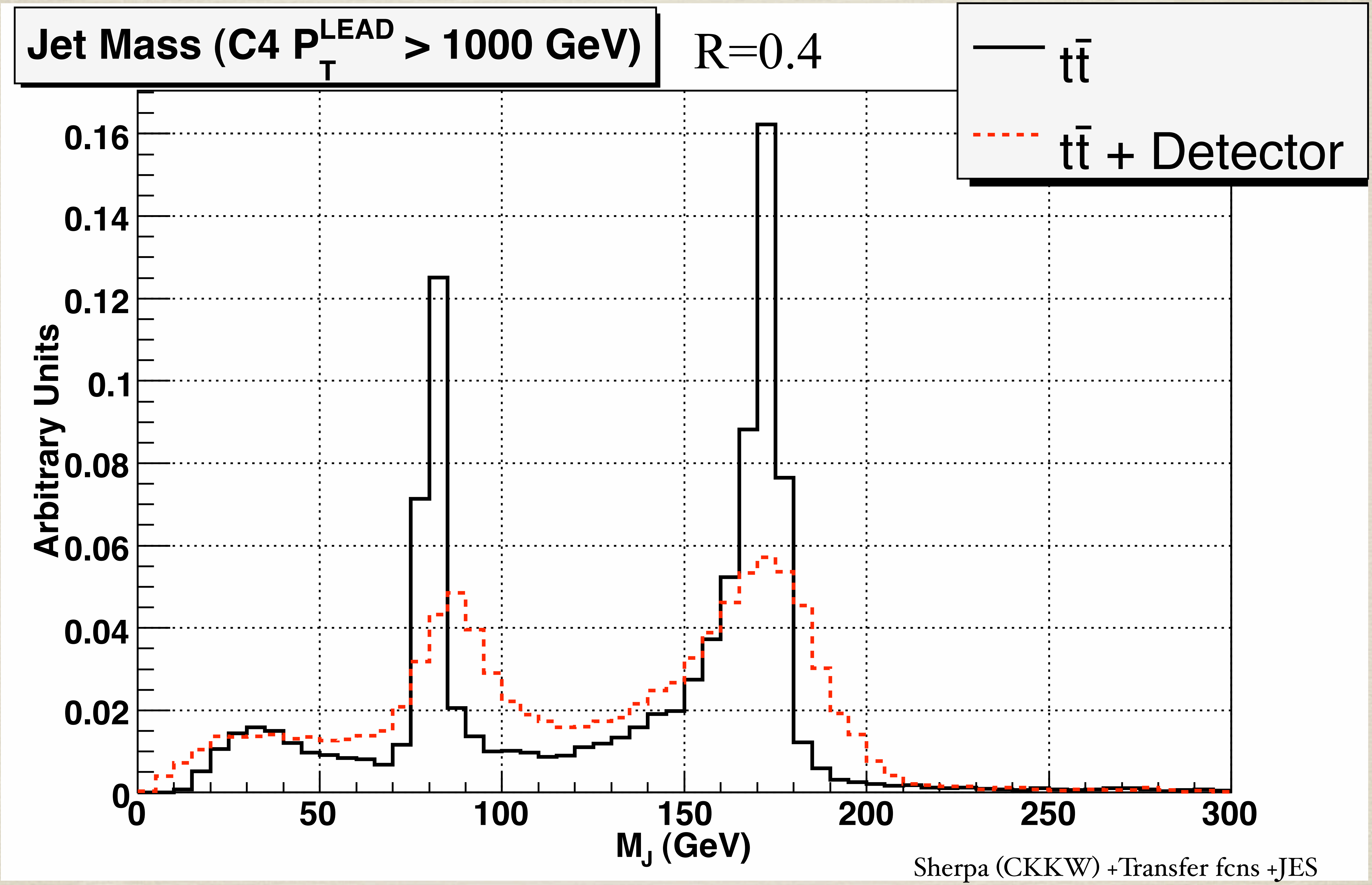
Top peak in jet mass ?

Top jets collimate @ high P_T



Cone Size: $R^2 = (\Delta\eta)^2 + (\Delta\phi)^2$

Top Jet Mass Distribution



Small cone losses signal

Top Jets @ the LHC

Mass Tag; Ilustrate with a Cone jet

$$R^2 = (\Delta\eta)^2 + (\Delta\phi)^2 \qquad m_J^2 = \left(\sum_{i\in R} P_i\right)^2$$

Top Mass Window: $140 \leq m_J \leq 210$ GeV

Counting in the mass window, seems hopeless...

$S/B \sim 10^{-2}$ For jets with $P_T > 1000GeV \;\; R = 0.4$

$$\begin{array}{cc} jj + X & t\bar{t} + X \\ 10pb & 100fb \end{array}$$

Need to Study the Background...

QCD Jet Mass Background, Theory

LA, Lee, Perez, Sung & Virzi (Berger, Kucs, Sterman)

Jet Production:
(due to light jets)

$$H_a(p_a) + H_b(p_b) \to J_1(m^2_{J_1}, p_{1,T}, R) + X$$

This x-section factorizes

$$\frac{d\sigma_{H_A H_B \to J_1 X}(R)}{dp_T dm_J d\eta} = \sum_{abc} \int dx_a\, dx_b\, \underbrace{\phi_a(x_a)\, \phi_b(x_b)}_{\text{pdf's}} \frac{d\hat{\sigma}_{ab\to cX}}{dp_T dm_J d\eta}(x_a, x_b, p_T, \eta, m_J, R)$$

for small R

$$\frac{d\sigma_{H_A H_B \to J_1 X}(R)}{dp_T dm_J d\eta} = \sum_{abc} \int dx_a\, dx_b\, \phi_a(x_a)\, \phi_b(x_b) \overbrace{H_{ab\to cX}(x_a, x_b, p_T, \eta, R)}^{\text{Hard}}$$
$$\times \underbrace{J_1^c(m_J, p_T, R).}_{\text{Jet functions}} + \mathcal{O}(R^2)$$

Contributions from initial state radiation to Jet mass $\sim R^2$

QCD Jet Mass distribution

Leading Contribution: Single Gluon Emission

$$J^{(f)} = 2\frac{\alpha_S}{\pi}\frac{C_f}{m_J}\log\left(\frac{p_T^2 R^2}{m_J^2}\right) + \mathcal{O}(R^4)$$

Jet Mass Distribution;

$$\frac{d\sigma(R)}{dp_T dm_J} = \sum_c J^c(m_J, p_T, R)\,\frac{d\hat{\sigma}^c(R)}{dp_T}$$

Jet Functions

Quarks jets

$$J_i^q(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2\sqrt{2}\,(p_{0,J_i})^2}\frac{\xi_\mu}{N_c}\sum_{N_{J_i}} \mathrm{Tr}\left\{\gamma^\mu \langle 0|q(0)\Phi_\xi^{(\bar{q})\dagger}(\infty,0)|N_{J_i}\rangle\langle N_{J_i}|\Phi_\xi^{(\bar{q})}(\infty,0)\bar{q}(0)|0\rangle\right\}$$

$$\times\delta\left(m_J^2 - \tilde{m}_J^2(N_{J_i},R)\right)\delta^{(2)}(\hat{n}-\tilde{n}(N_{J_i}))\delta(p_{0,J_i}-\omega(N_{J_c})),$$

Gluons jets

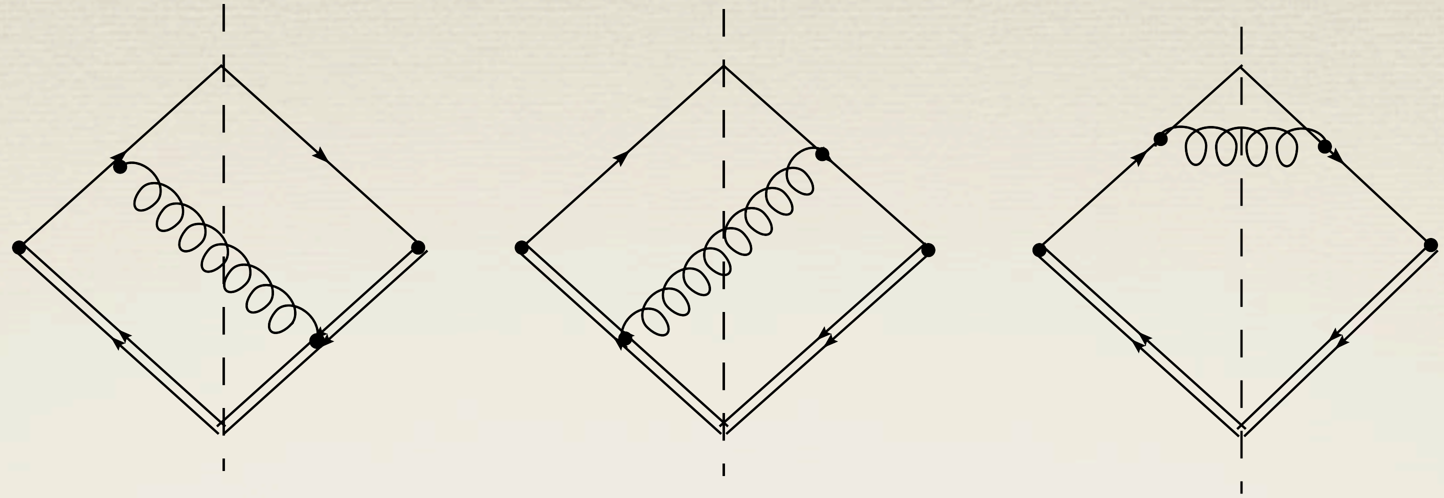
$$J_i^g(m_J^2, p_{0,J_i}, R) = \frac{(2\pi)^3}{2(p_{0,J_i})^3}\sum_{N_{J_i}}\langle 0|\xi_\sigma F^{\sigma\nu}(0)\Phi_\xi^{(g)\dagger}(0,\infty)|N_{J_i}\rangle\langle N_{J_i}|\Phi_\xi^{(g)}(0,\infty)F_\nu{}^\rho(0)\xi_\rho|0\rangle$$

$$\times\delta\left(m_J^2 - \tilde{m}_J^2(N_{J_i},R)\right)\delta^{(2)}(\hat{n}-\tilde{n}(N_{J_i}))\delta(p_{0,J_i}-\omega(N_{J_c})).$$

Normalized $\int dm_J J(m_J) = 1$

Perturbatively Calculable; systematically improvable

Quark Jet Function, in detail...



(a) (b) (c)

$$J_i^{q(1)}(m_J^2, p_{0,J_i}, R) \;=\; \frac{C_F\beta_i}{4m_{J_i}^2}\int_{\cos(R)}^{\beta_i}\frac{d\cos\theta_S}{\pi}\frac{\alpha_S(k_0)\,z^4}{(2(1-\beta_i\cos\theta_S)-z^2)\,(1-\beta_i\cos\theta_S)}\times$$
$$\left\{z^2\frac{(1+\cos\theta_S)^2}{(1-\beta_i\cos\theta_S)}\frac{1}{(2(1+\beta_i)(1-\beta_i\cos\theta_S)-z^2(1+\cos\theta_S))}+\right.$$
$$\left.\frac{3(1+\beta_i)}{z^2}+\frac{1}{z^4}\frac{(2(1+\beta_i)(1-\beta_i\cos\theta_S)-z^2(1+\cos\theta_S))^2}{(1+\cos\theta_S)(1-\beta_i\cos\theta_S)}\right\},$$

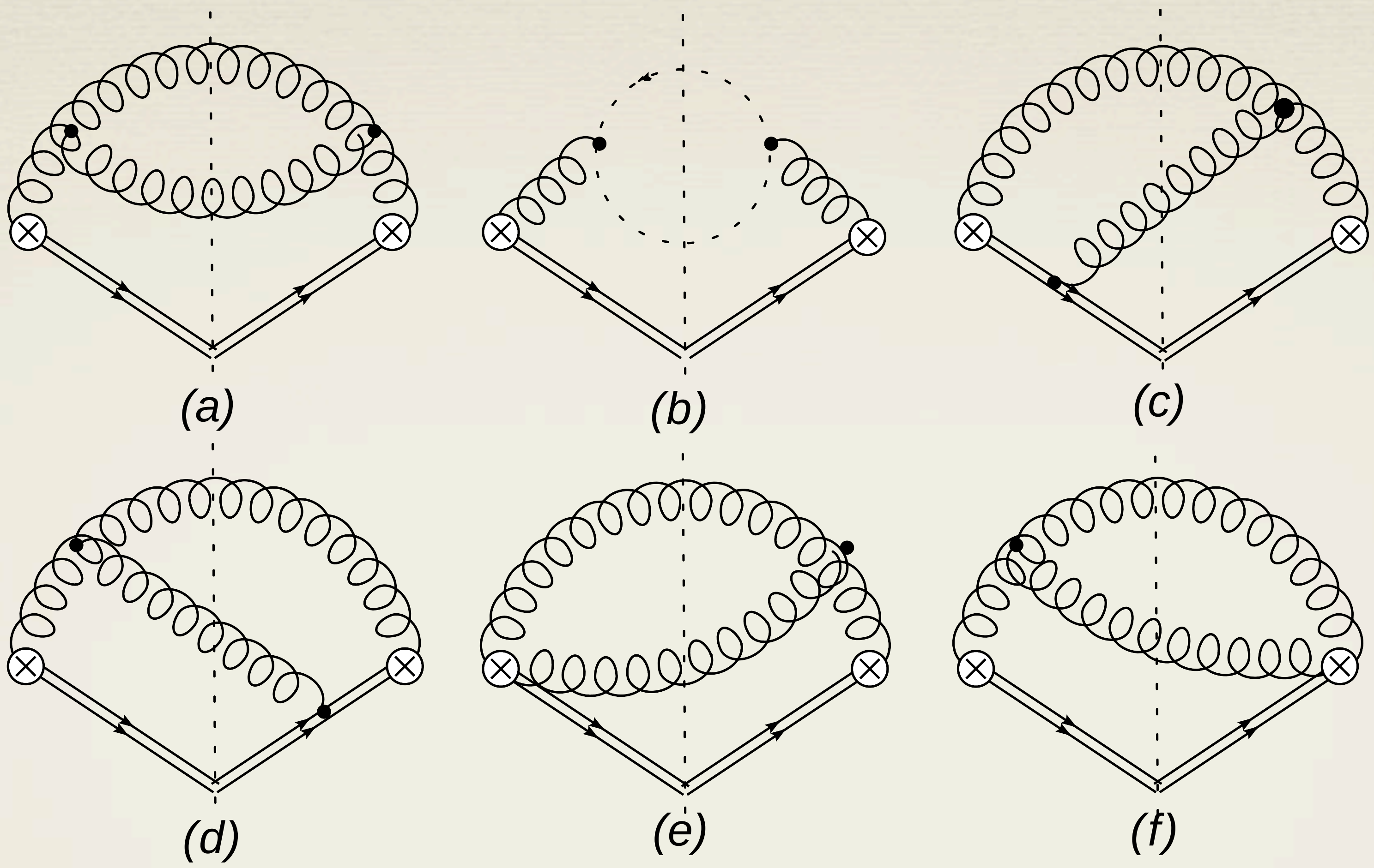
$$z = m_J/p_{0,J_i}$$

θ_S : Angle between Jet axis and softer particle

$$\beta_i = \sqrt{1-z^2}$$

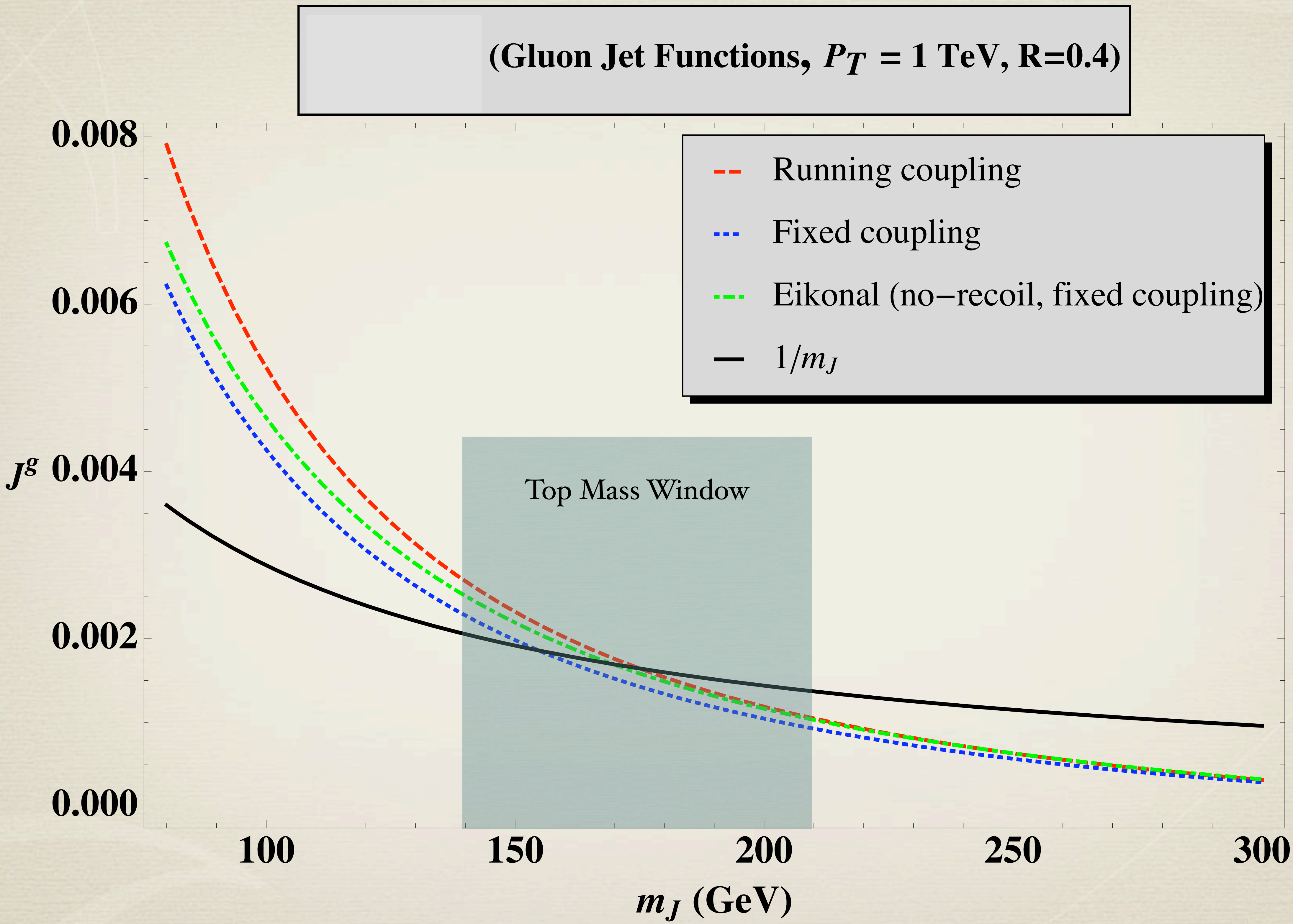
$$k_0 = \frac{p_{0,J}}{2}\frac{z^2}{1-\beta_i\cos\theta_S}$$

Gluon Jet function in detail...



$$J_i^{g(1)}(m_J^2, p_{0,J_i}, R) \quad = \quad \frac{C_A \beta_i}{16 m_{J_i}^2} \int_{\cos(R)}^{\beta_i} \frac{d\cos\theta_S}{\pi} \frac{\alpha_S(k_0)}{(1-\beta\cos\theta_S)^2(1-\cos^2\theta_S)(2(1+\beta)-z^2)}$$
$$\times\left(z^4(1+\cos\theta_S)^2 + z^2(1-\cos^2\theta_S)(2(1+\beta_i)-z^2) + (1-\cos\theta_S)^2(2(1+\beta_i)-z^2)^2\right)^2.$$

The Importance of the log



QCD Jet Mass distribution

Jet functions defined as to not affect the Total X-section.

Background data would be an admixture of quarks and gluons Jets

Model Background Data:

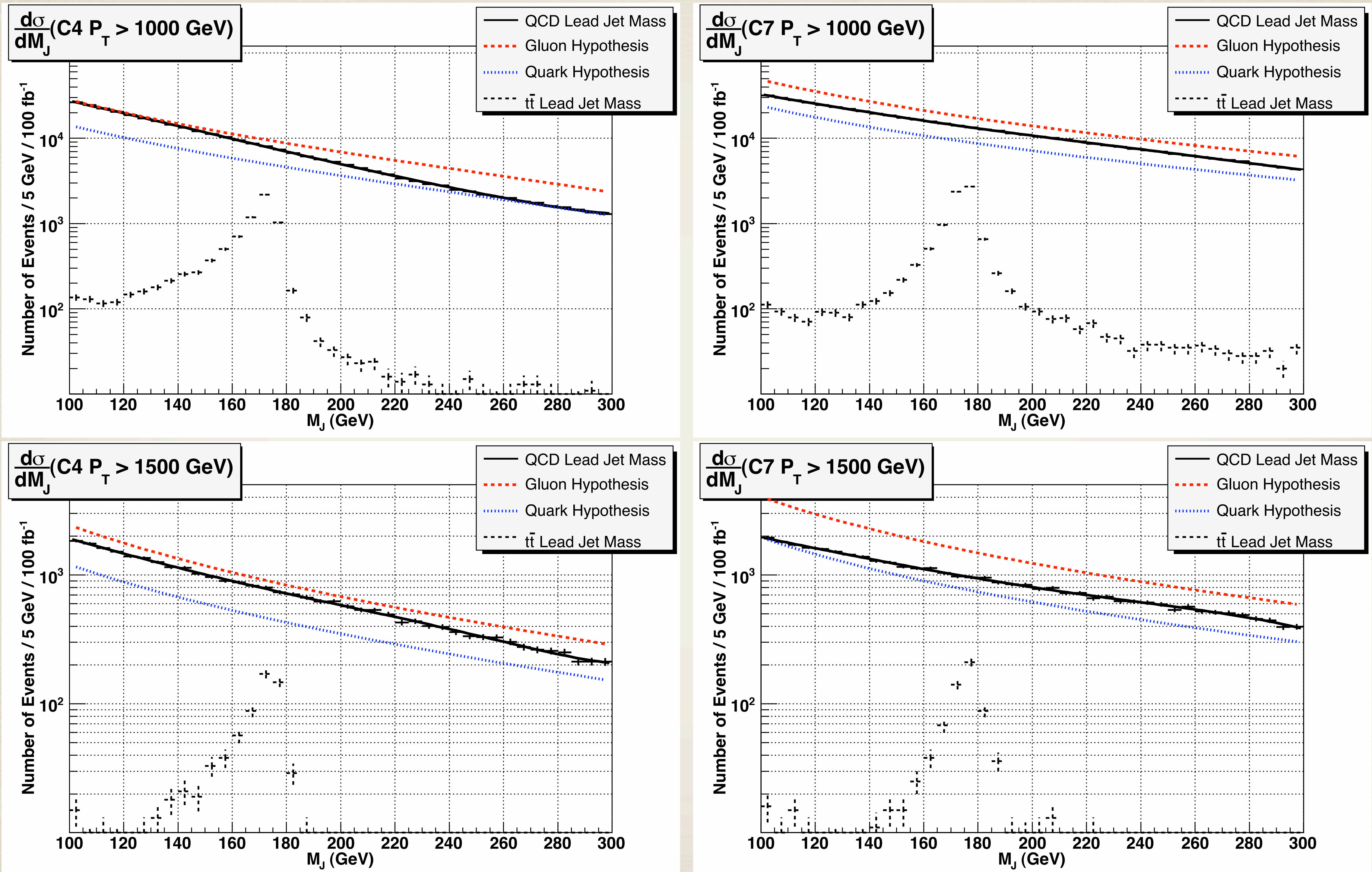
$$\frac{d\sigma_B}{dm_J dp_T} = B(m_J)\frac{d\sigma_{tot}}{dp_T}$$

$$B(m_J) = \kappa(m_J)J^{(q)}(m_J) + (1-\kappa(m_J))J^{(g)}$$

$$\kappa(m_J) = \kappa_0 + \kappa_1 \frac{m_J}{p_T^{\min} R}$$

2 param fit

Ex: (from sherpa) Di-Jet Vs. SM $t\bar{t}$

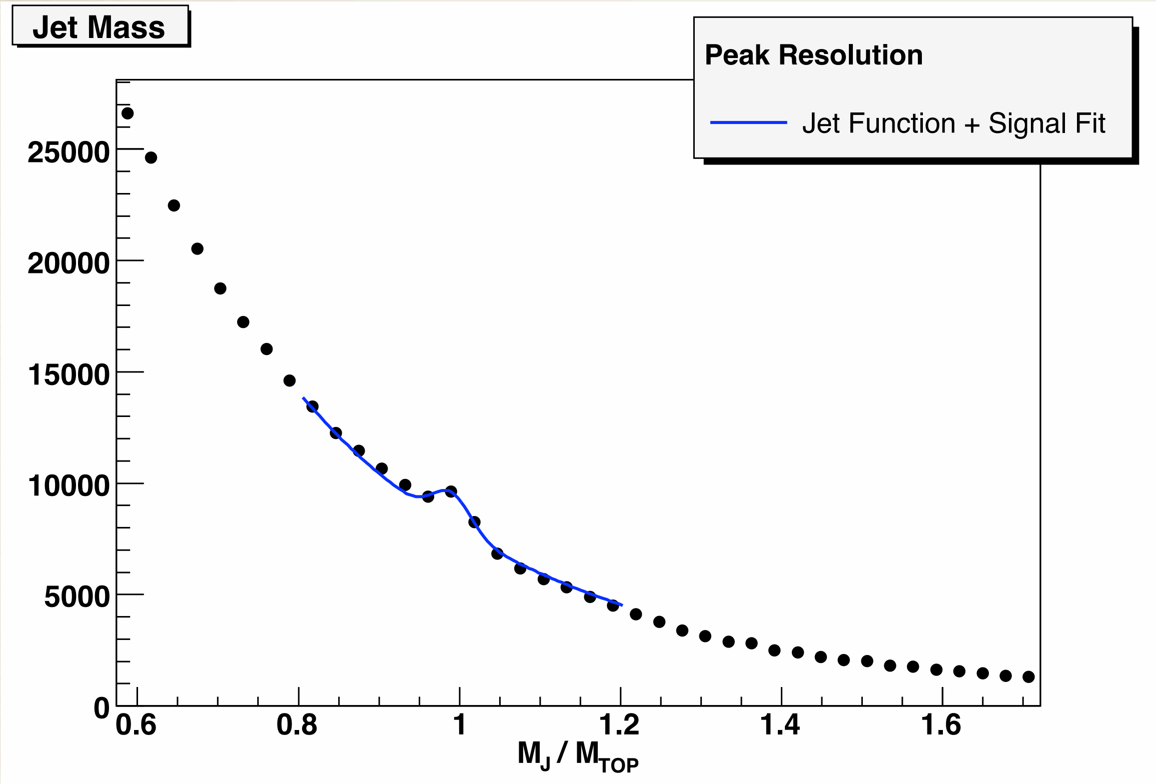


Ex: (from sherpa) Di-Jet Vs. SM $t\bar{t}$

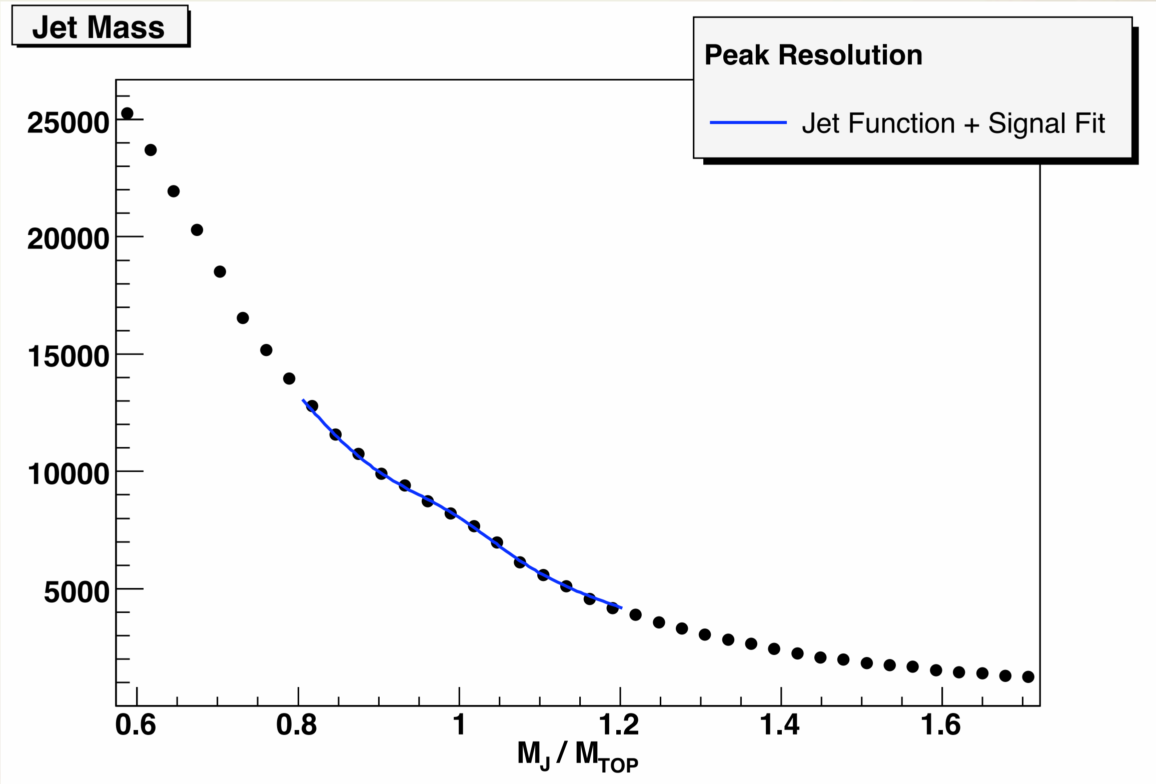
Side-band Analysis with our Ansatz for the Background

Maximum likelihood fit. Back+Signal

$$(p_T^{\min} = 1TeV, R = 0.7)$$



Background + Signal



Background + Signal
+Detector effects

Signal Significance

$p_T{}^{lead} \geq 1000\,\mathrm{GeV}$ Cone $R = 0.7$ $25 fb^{-1}$

JES	B_{FIT}	S_{FIT}	ΔS	n_σ	p-value	χ^2/ndf	$(S/B)_{\mathrm{FIT}}$
0%	47277	2730	399	6.8	0.98	0.38	0.058
5%	54870	3419	424	8.1	0.87	0.60	0.062
-5%	37910	2274	354	6.4	1.00	0.21	0.060

significance

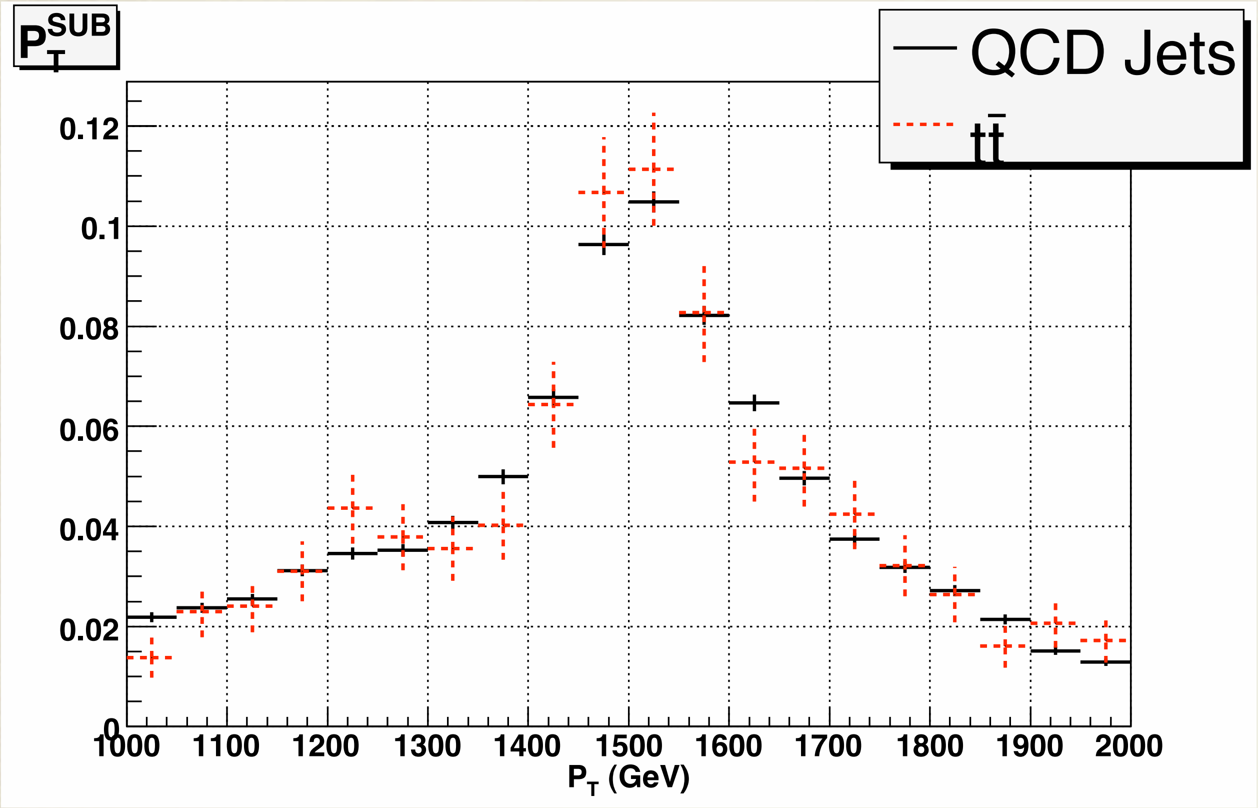
$p_T{}^{lead} \geq 1500\,\mathrm{GeV}$ Cone $R = 0.7$ $100 fb^{-1}$

JES	B_{FIT}	S_{FIT}	ΔS	n_σ	p-value	χ^2/ndf	$(S/B)_{\mathrm{FIT}}$
0%	18456	1045	252	4.2	0.75	0.72	0.057
5%	24921	1559	284	5.4	0.96	0.45	0.063
-5%	13315	693	213	3.3	1.00	0.20	0.052

S_{FIT} and B_{FIT} are the results of an extended maximum likelihood fit. ΔS is the error on S_{FIT}

Double mass-tagging

Add a Mass tag on the subleading jet.



$$p_T{}^{lead} \geq 1500\,\text{GeV}$$

$p_T{}^{lead} \geq 1500\,\text{GeV}$ Cone $R = 0.4$ $100\,fb^{-1}$

JES	B_{FIT}	S_{FIT}	ΔS	n_σ	p-value	χ^2/ndf	$(S/B)_{\text{FIT}}$
0%	2341	430	94	4.6	0.99	0.35	0.184
5%	2968	624	110	5.7	0.96	0.45	0.210
-5%	1593	436	79	5.5	0.82	0.66	0.274

Summary

Jet functions provide a systematic approach to describe the jet mass background

Ex: SM Top Reach (without b-tagging, nor jet structure)

$$p_T^{\text{min}} \begin{array}{l} \sim 1.0 \text{ TeV top-jet with } 25 fb^{-1} \\ \sim 1.5 \text{ TeV top-jet pairs with } 100 fb^{-1} \end{array}$$

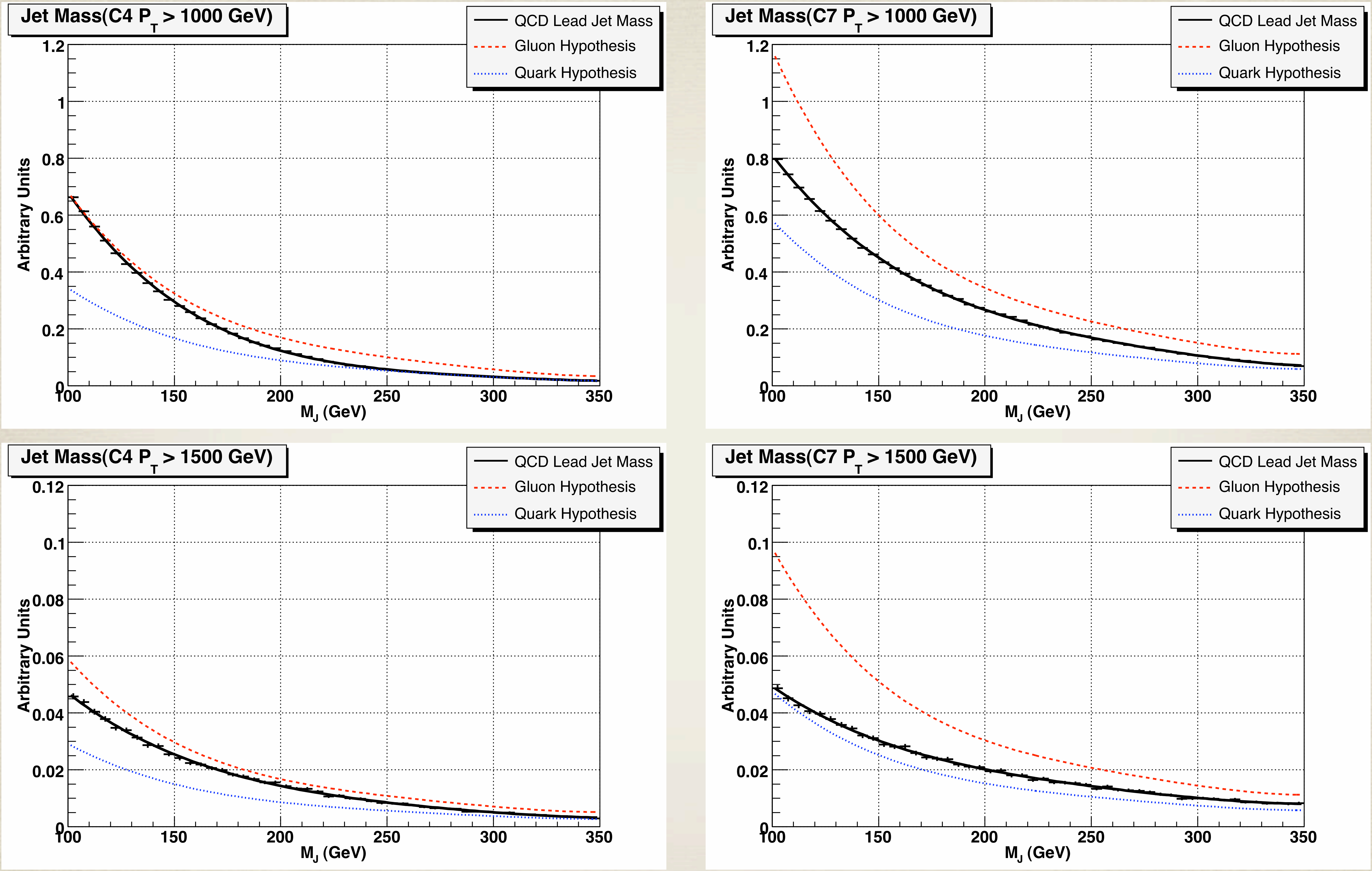
Portability: Can be improved by higher orders,
Resummation techniques,
Soft contributions.

Jet functions can even be used to understand Structure of Jets. Leading to New Observables that can suppress the background further.

LA, S. J. Lee, G. Perez, G. Sterman, I. Sung, and J. Virzi

Back up

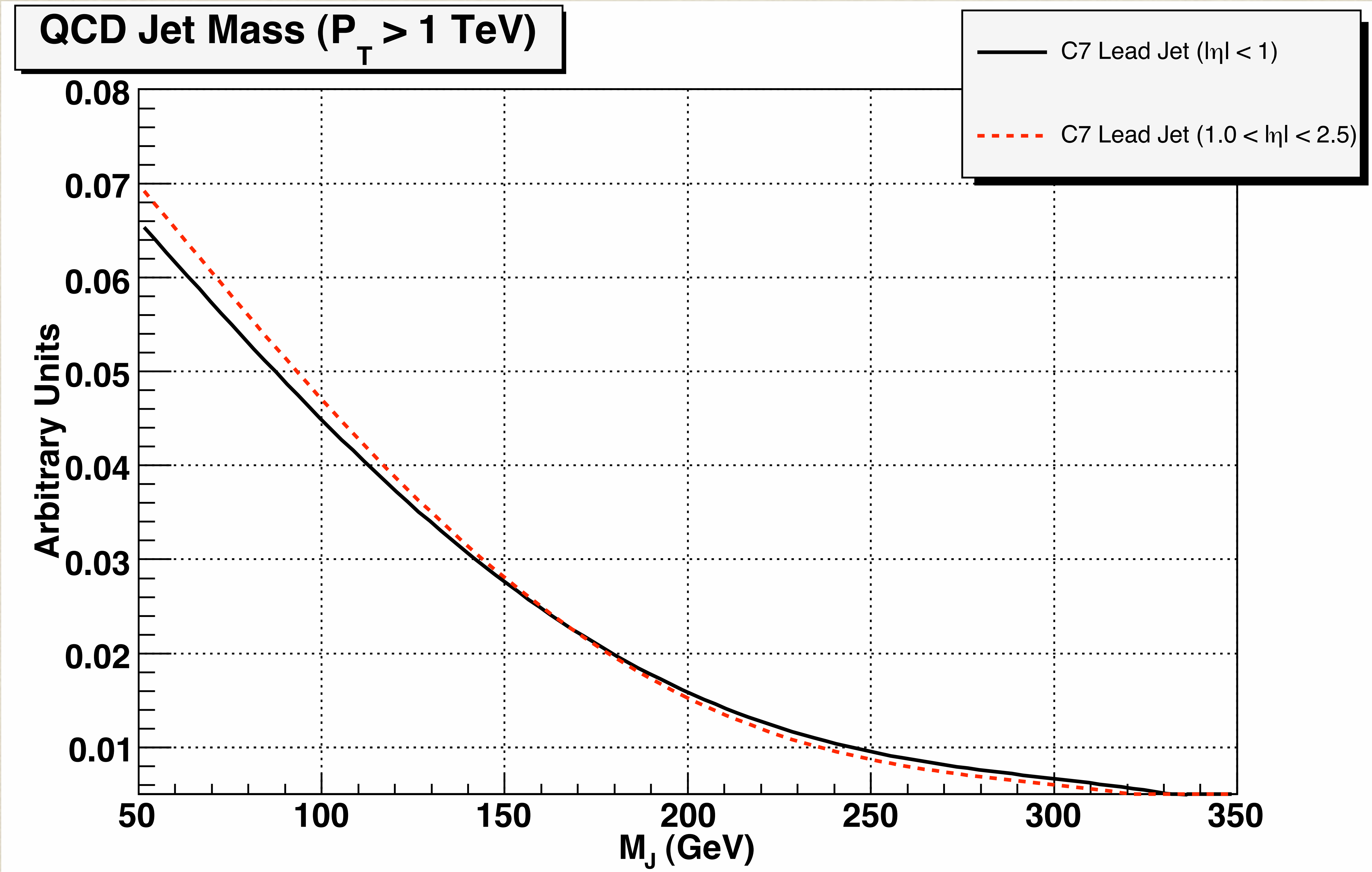
Theory Vs. MC

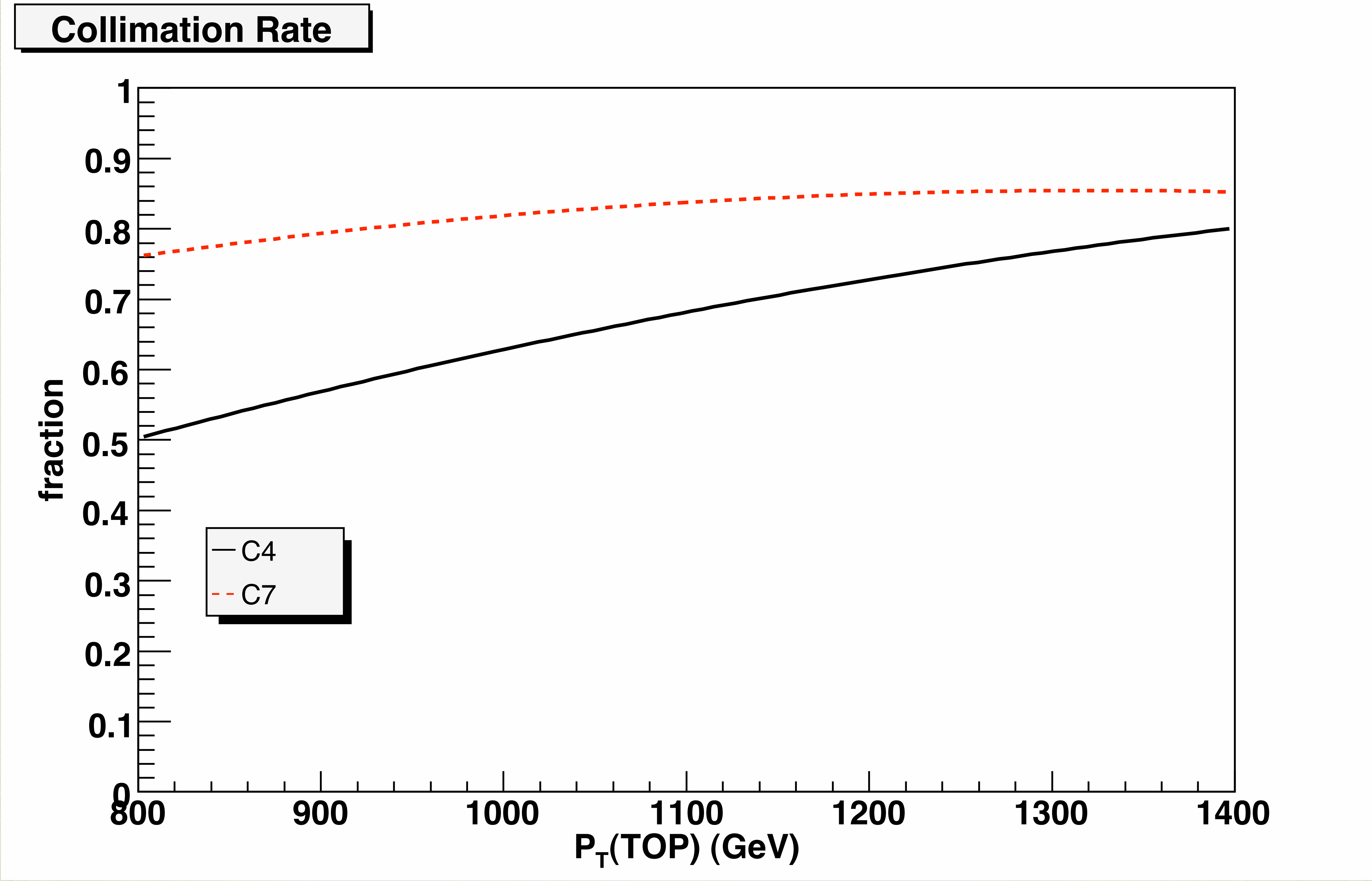


LA, Lee, Perez, Sung & Virzi

Process	Generator	PDF	Matching	Cross Section
$pp \to t\bar{t}(j)$	SHERPA 1.0.9	CTEQ6M	CKKW	135 fb
$pp \to t\bar{t}(j)$	SHERPA 1.1.2	CTEQ6M	CKKW	149 fb
$pp \to t\bar{t}(j)$	MG/ME 4	CTEQ6M	MLM	68 fb
$pp \to t\bar{t}(j)$	MG/ME 4	CTEQ6L	MLM	56 fb
$pp \to t\bar{t}$	Pythia 6.4	CTEQ6L	-	157 fb
$pp \to t\bar{t}$	Pythia 8.1	CTEQ6M	-	174 fb
$pp \to jj(j)$	SHERPA 1.1.0	CTEQ6M	CKKW	10.2 pb
$pp \to jj(j)$	MG/ME 4	CTEQ6L	MLM	8.54 pb
$pp \to jj(j)$	MG/ME 4	CTEQ6M	MLM	9.93 pb
$pp \to jj$	Pythia 6.4	CTEQ6L	-	13.7 pb
$pp \to jj$	Pythia 8.1	CTEQ6M	-	13.3 pb

Table 1: Cross sections for producing final state $R = 0.4$ leading cone jets with $p_T \geq 1\,\text{TeV}$ and $|\eta| \leq 2$. Generation level cuts were imposed as follows. Final state partons from the hard scatter were required to have $p_T \geq 20\,\text{GeV}$. For MG/ME, final state partons have $|\eta| \leq 4.5$. Processes with a trailing (j) suffix indicate that $2 \to 2$ and $2 \to 3$ processes are represented.


QCD Jet Mass (P_T > 1 TeV)
C7 Lead Jet (|η| < 1)
C7 Lead Jet (1.0 < |η| < 2.5)
Arbitrary Units
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
50
100
150
200
250
300
350
M_J (GeV)


Collimation Rate
fraction
P_T(TOP) (GeV)
C4
C7
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
800
900
1000
1100
1200
1300
1400

Jet Substructure